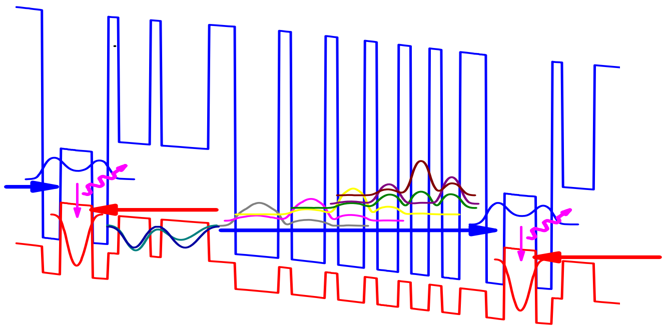
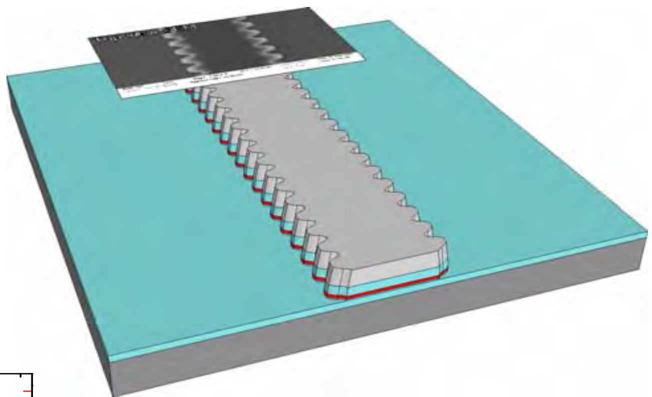
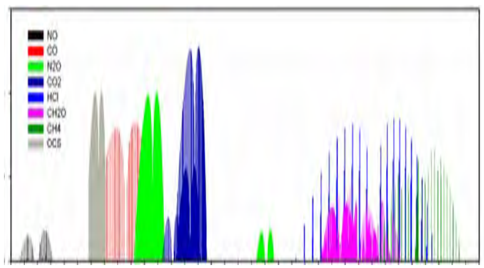
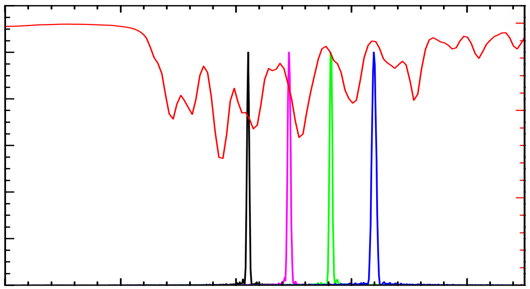
INTERBAND CASCADE LASERS FOR SPECTROSCOPY WITH VERY LOW INPUT POWER









Laser Applications to Chemical, Security, and Environmental Analysis
(San Diego CA, 30 January 2012)

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Standard Form 298 (Rev. 8-98)
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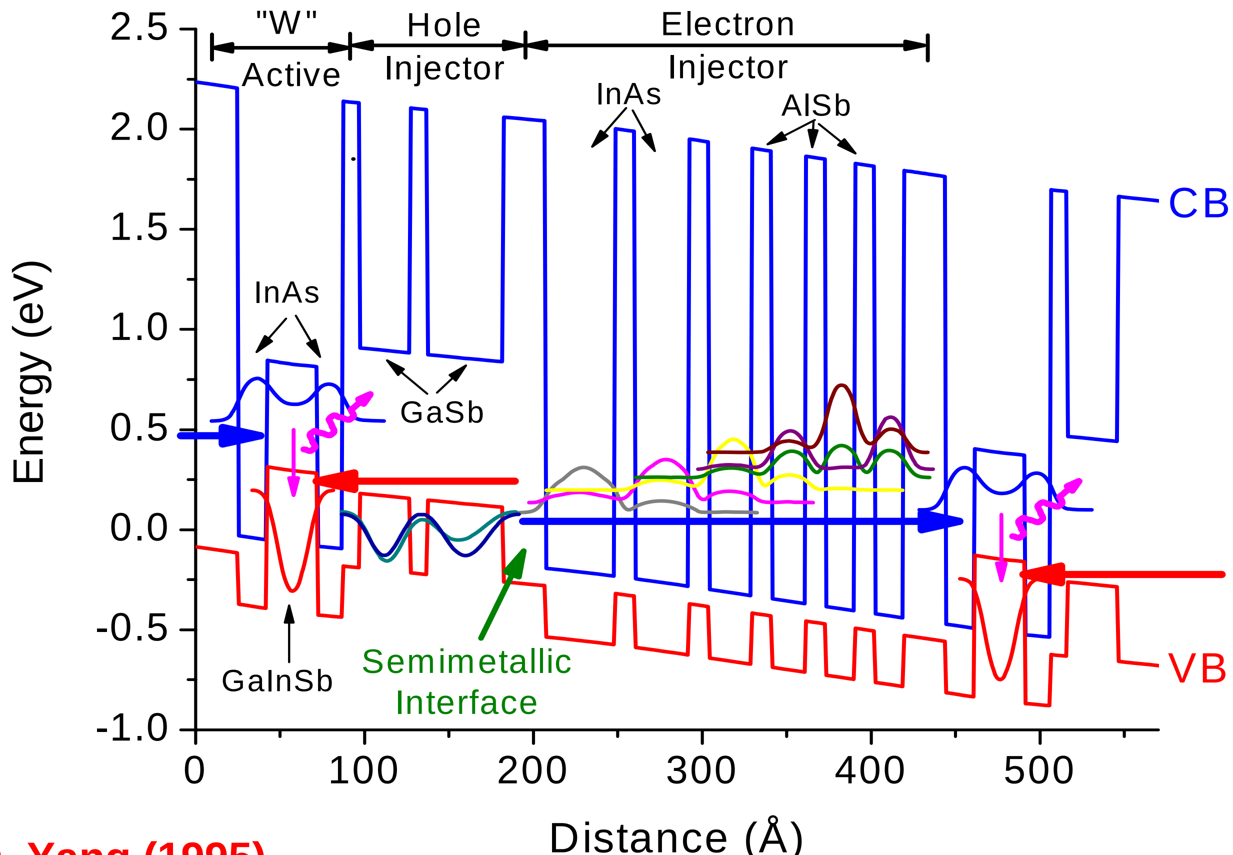
THE INTERBAND CASCADE LASER (ICL)

Hybrid of conventional diode (*Interband* active transitions) & QCL (*Cascaded* multiple stages)



1st Proposed: **R. Q. Yang (1995)**

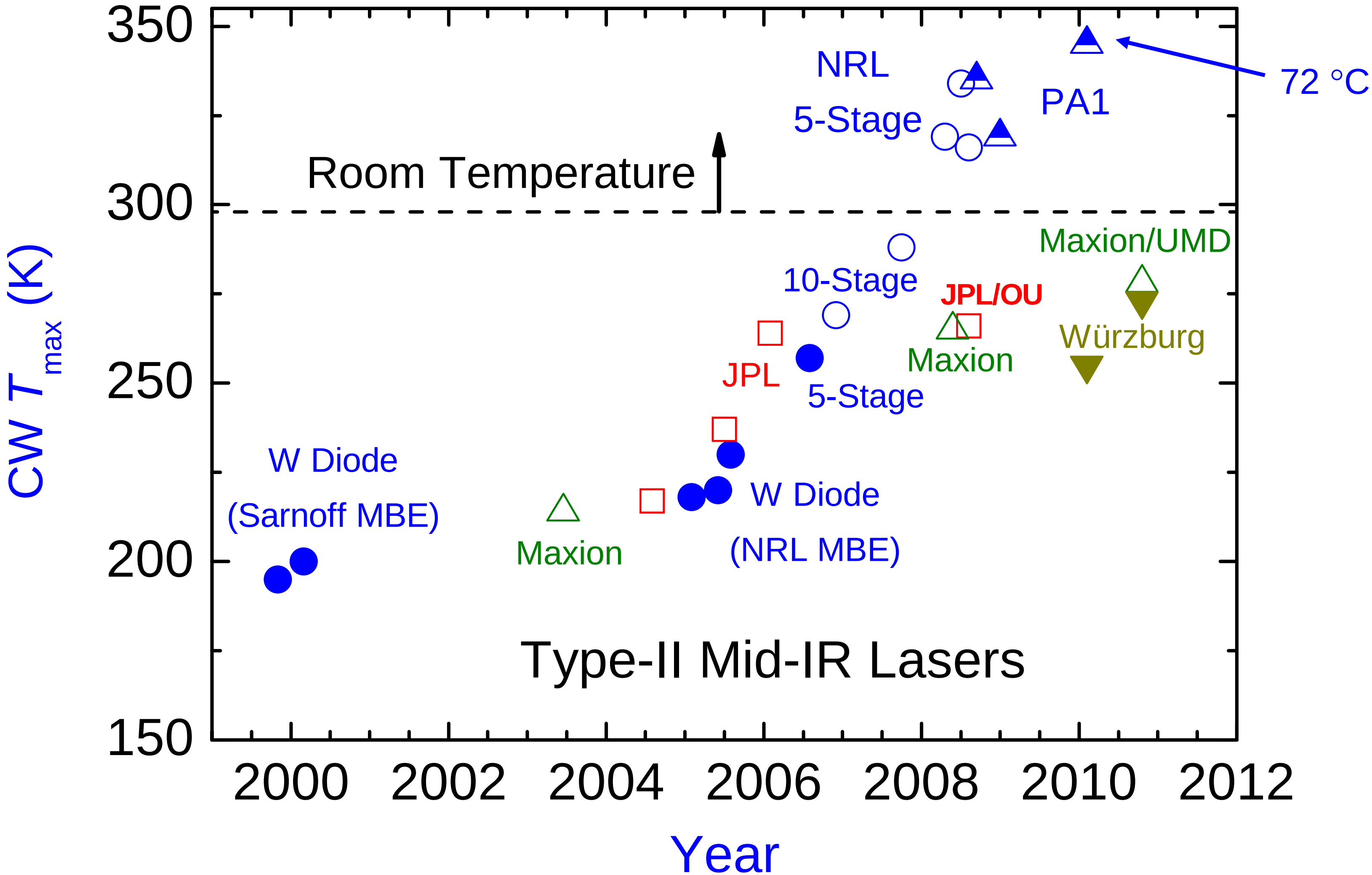
Design Improvements: **Meyer & Vurgaftman (1996-1997)**

1st Experimental Demo: **U. Houston & Sandia (1997)**

Further Developed: **ARL, Maxion, JPL, U. Oklahoma, U. Würzburg**

1st NRL ICL: **August 2005**

BEYOND THE ROOM-TEMPERATURE BARRIER

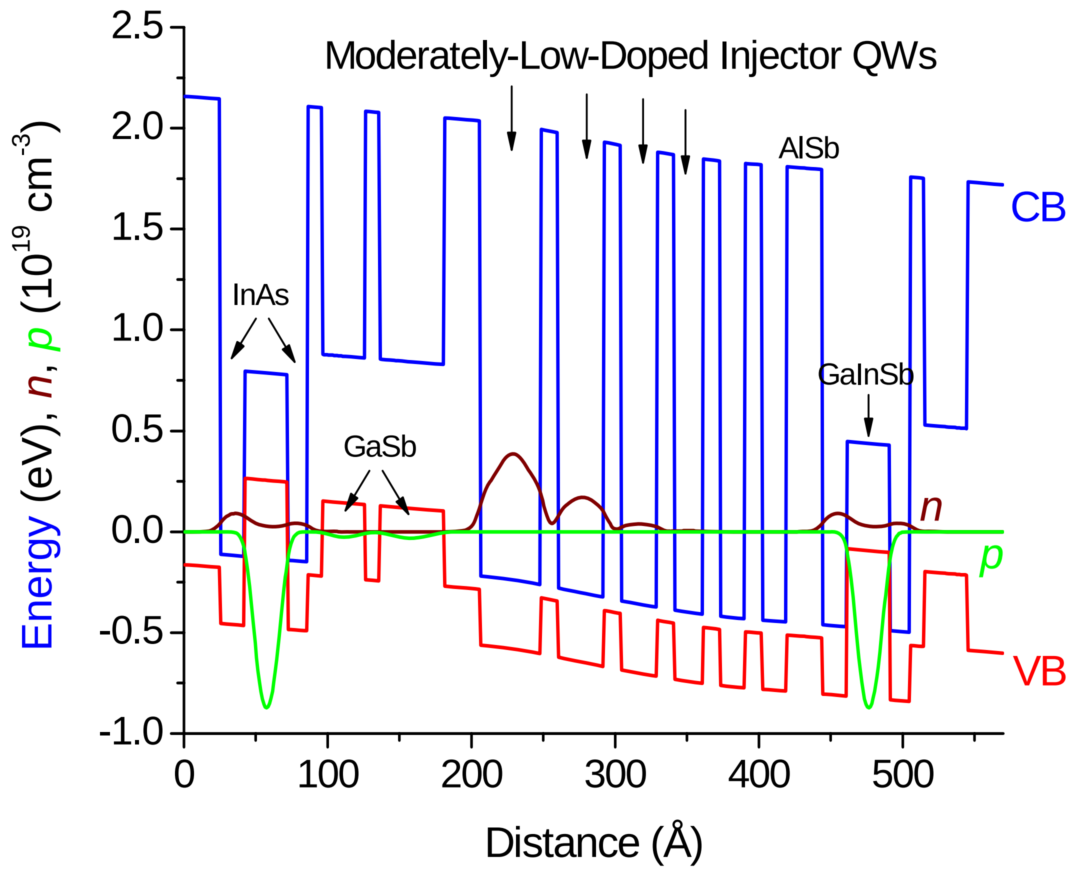


With thresholds reduced to ≈ 400 A/cm² by 2008, RT cw became routine

Were we approaching the fundamental limit?

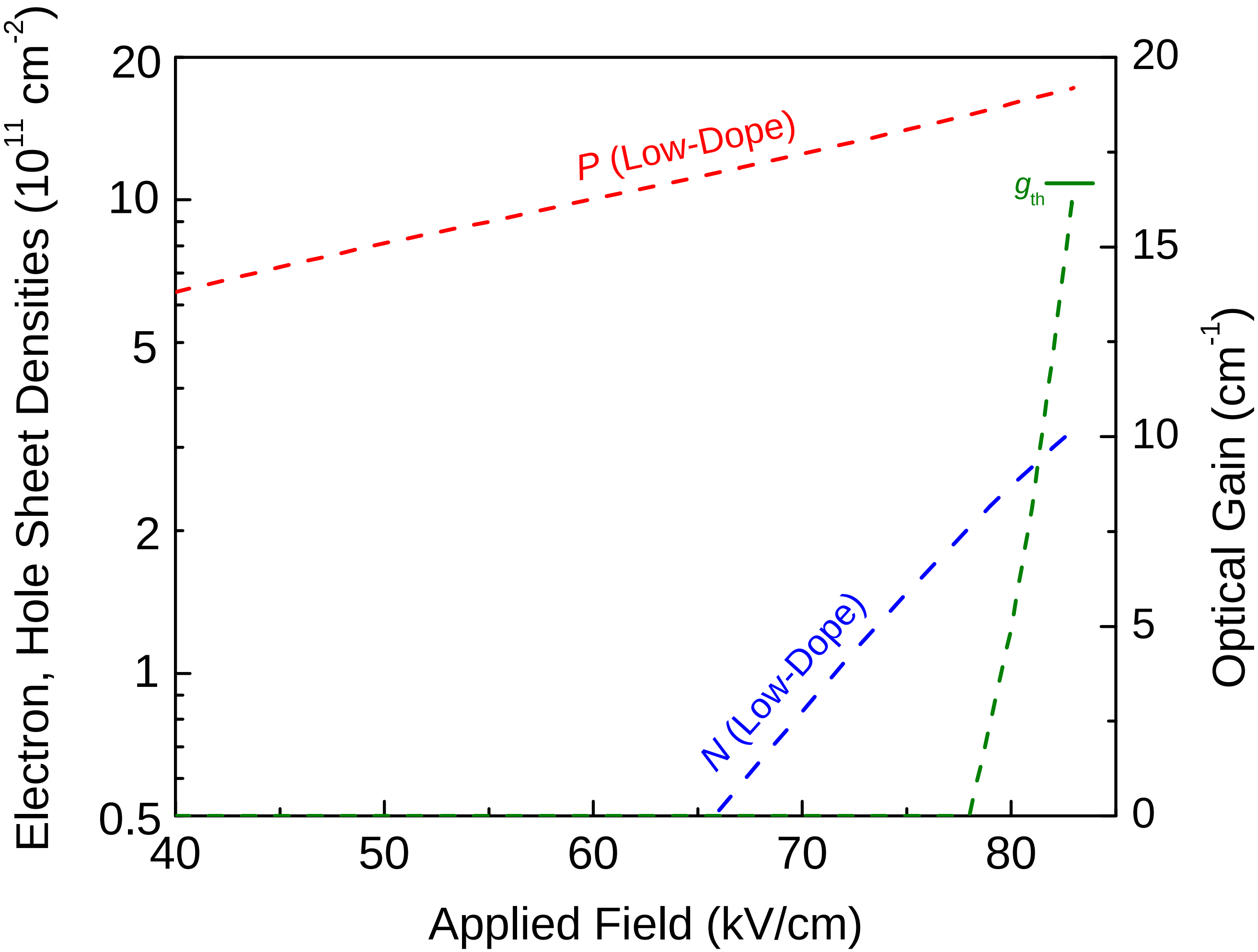
NO! – A SIGNIFICANT DESIGN FLAW REMAINED

Simulations revealed that conventional designs with moderate n-doping (≈ 4 x 10^{17} cm^{-3}) of injector QWs suffered from serious hole/electron population imbalance in active QWs



Even though more electrons than holes throughout the stage (due to doping), most electrons populated the injector while most holes populated the active QWs

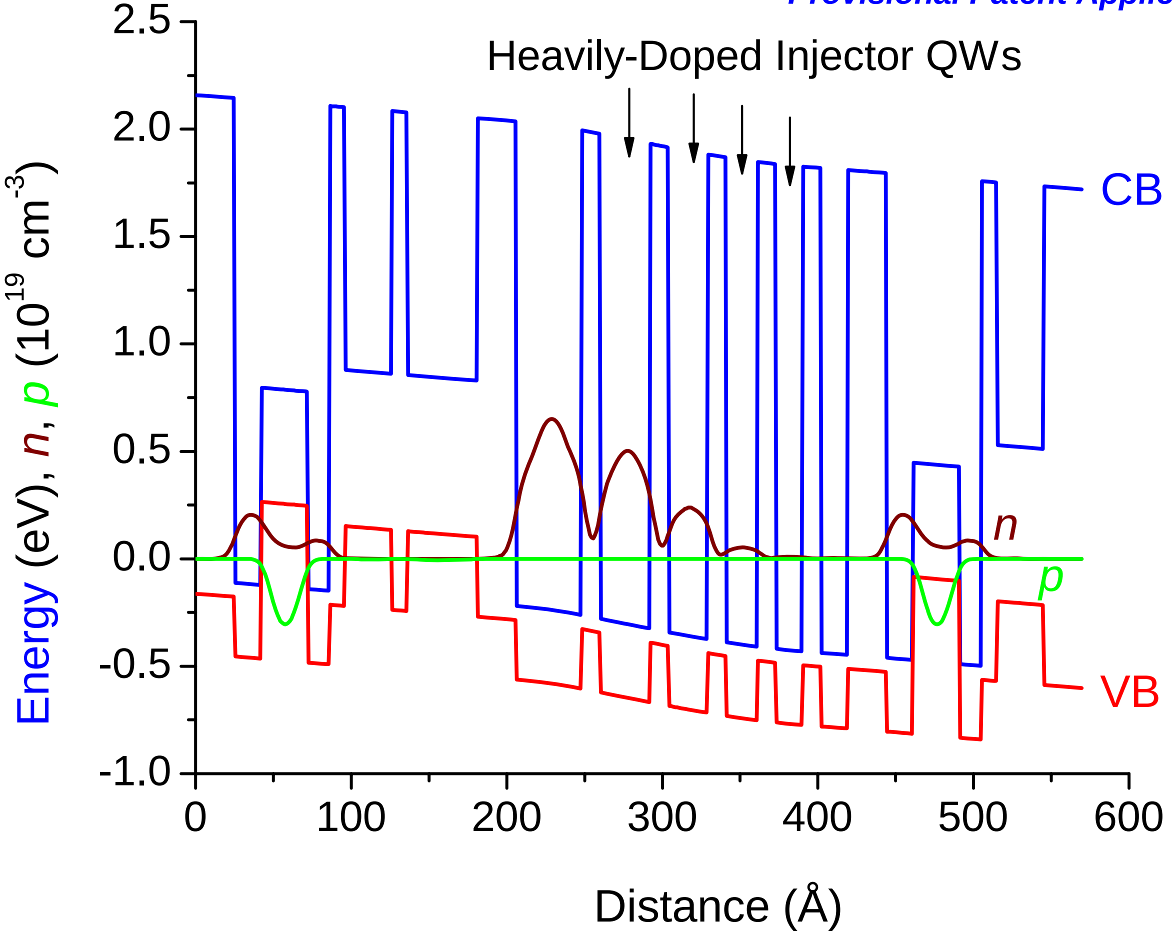
DENSITIES & GAIN vs. BIAS (CONVENTIONAL)



> 5x more holes than electrons in active QWs at threshold – Consequence is excessive internal losses & Auger non-radiative decay

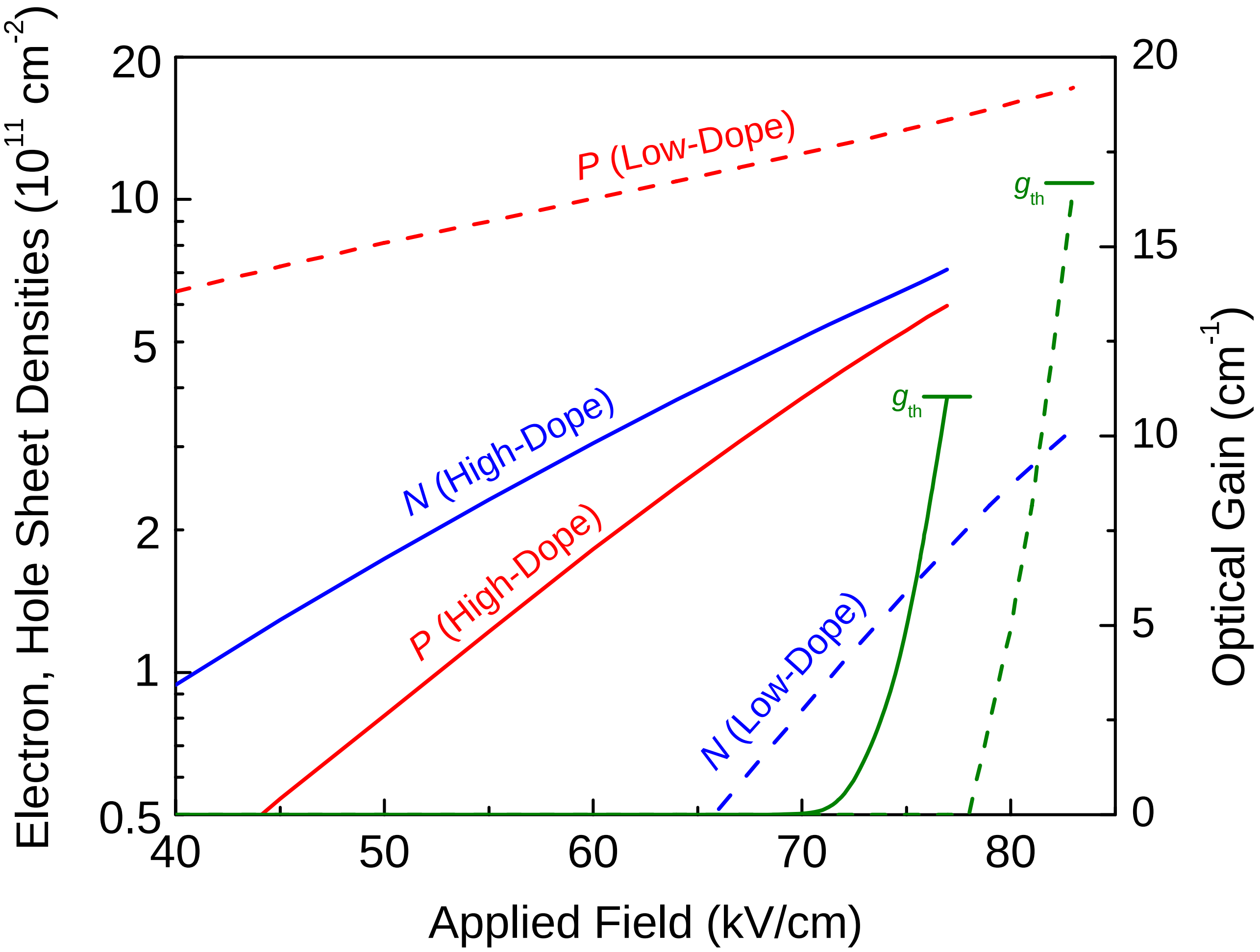
SOLUTION: INCREASE INJECTOR DOPING LEVEL BY > ORDER OF MAGNITUDE

[Vurgaftman et al., Nature Com., December 2011; U.S. Provisional Patent Application No. 61477191 (2011)]



Heavy n-doping of injector "rebalances" active electron & hole populations, to make them roughly equal

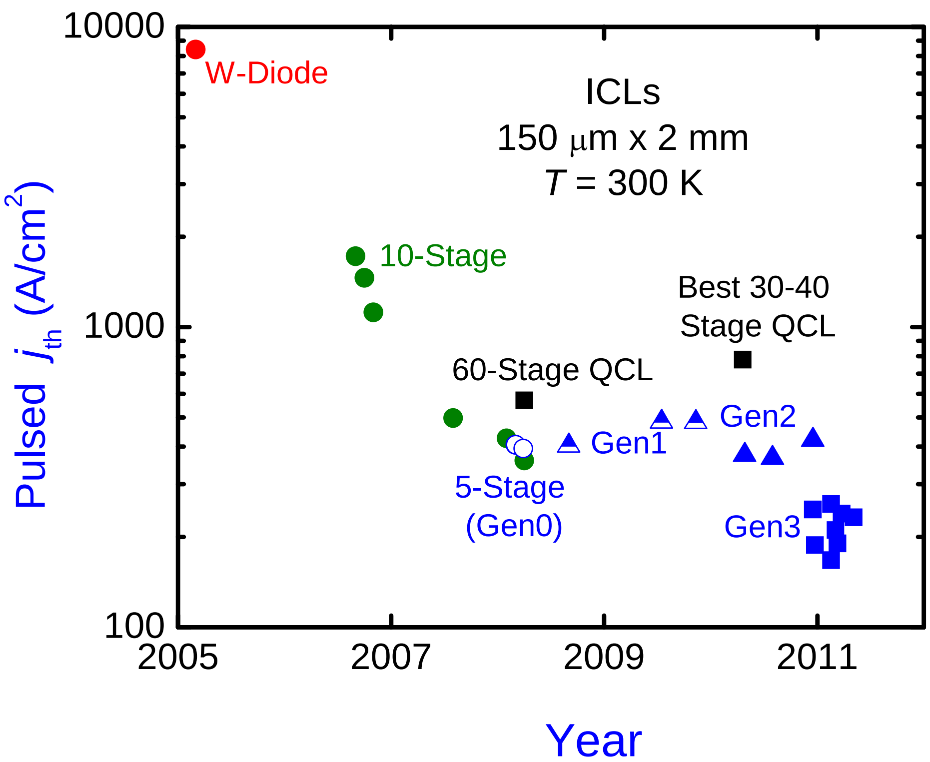
DENSITIES & GAIN vs. BIAS (REBALANCED)



Simulations predicted that rebalancing should enable lasing at much lower carrier concentration, plus longer Auger lifetime & lower loss (because much lower P_{th})

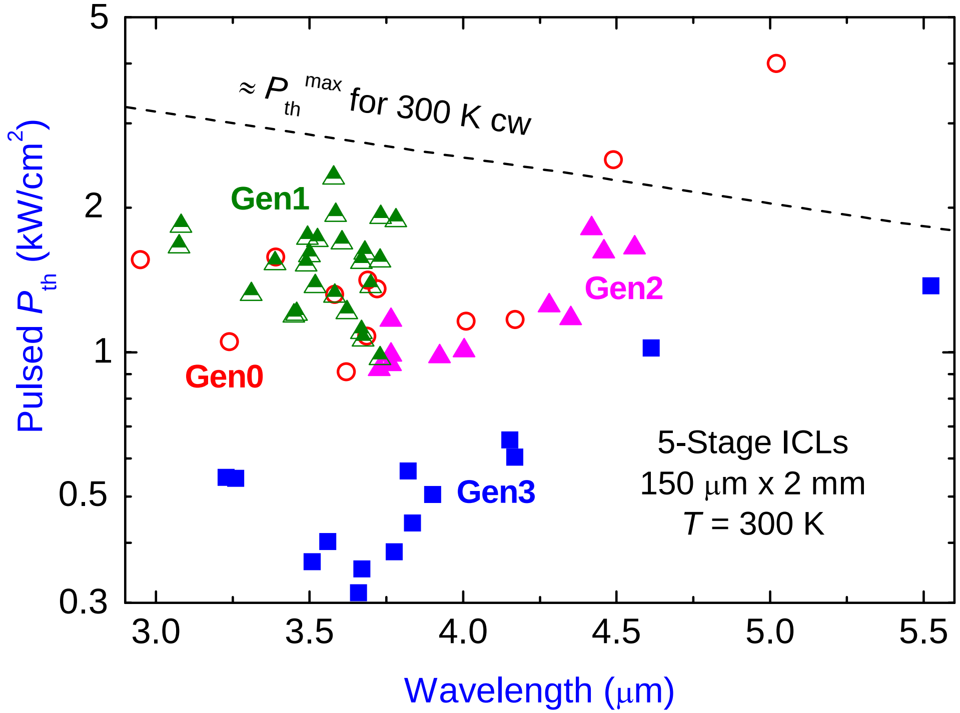
REBALANCING (Gen3) SUBSTANTIALLY REDUCES EXPERIMENTAL THRESHOLDS

All Gen3 devices significantly out-perform all previous ICLs



What really matters is:

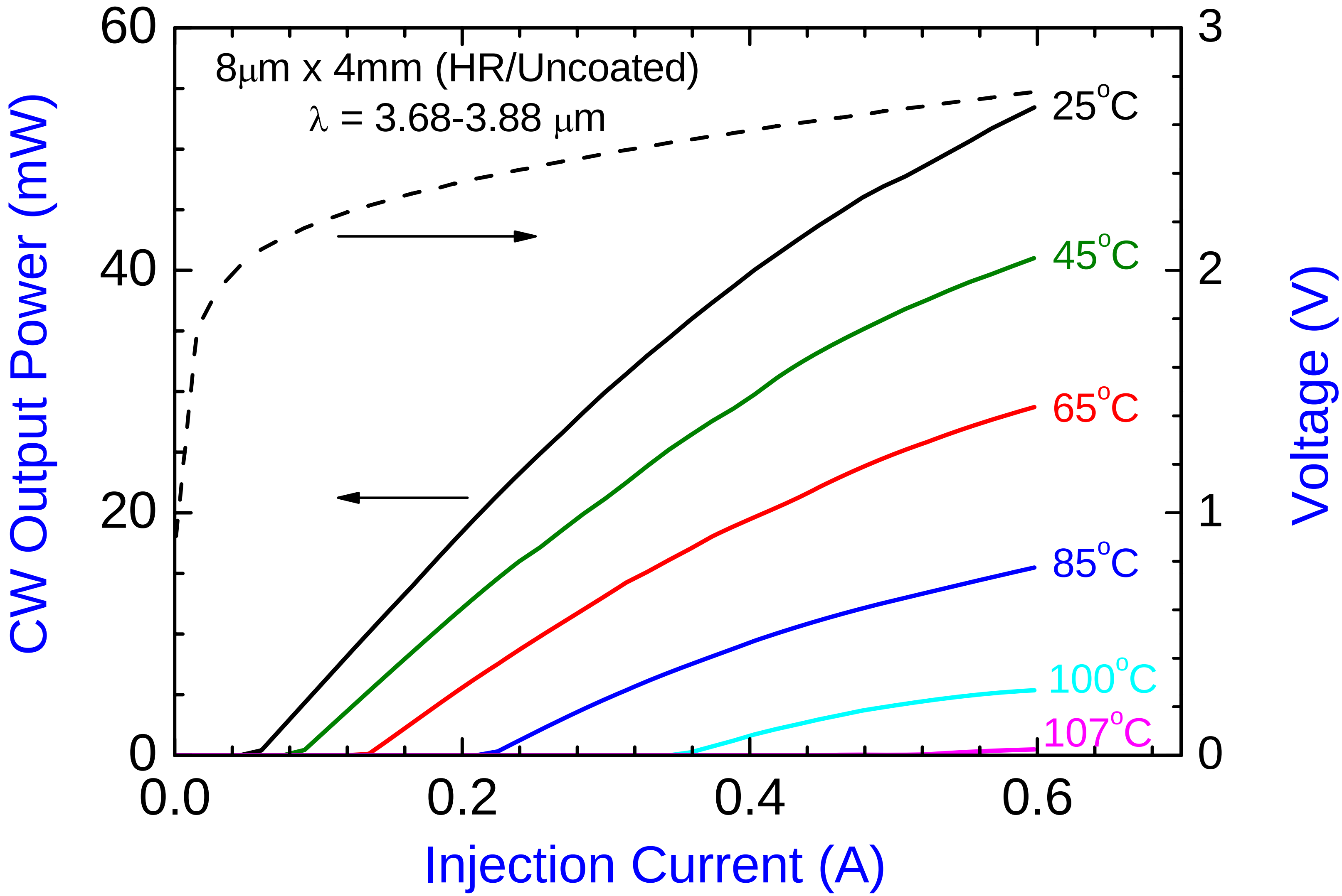
$P_{th} = V_{th} \times j_{th}$



Lower power dissipation means longer battery lifetime (to λ > 5 μm!)

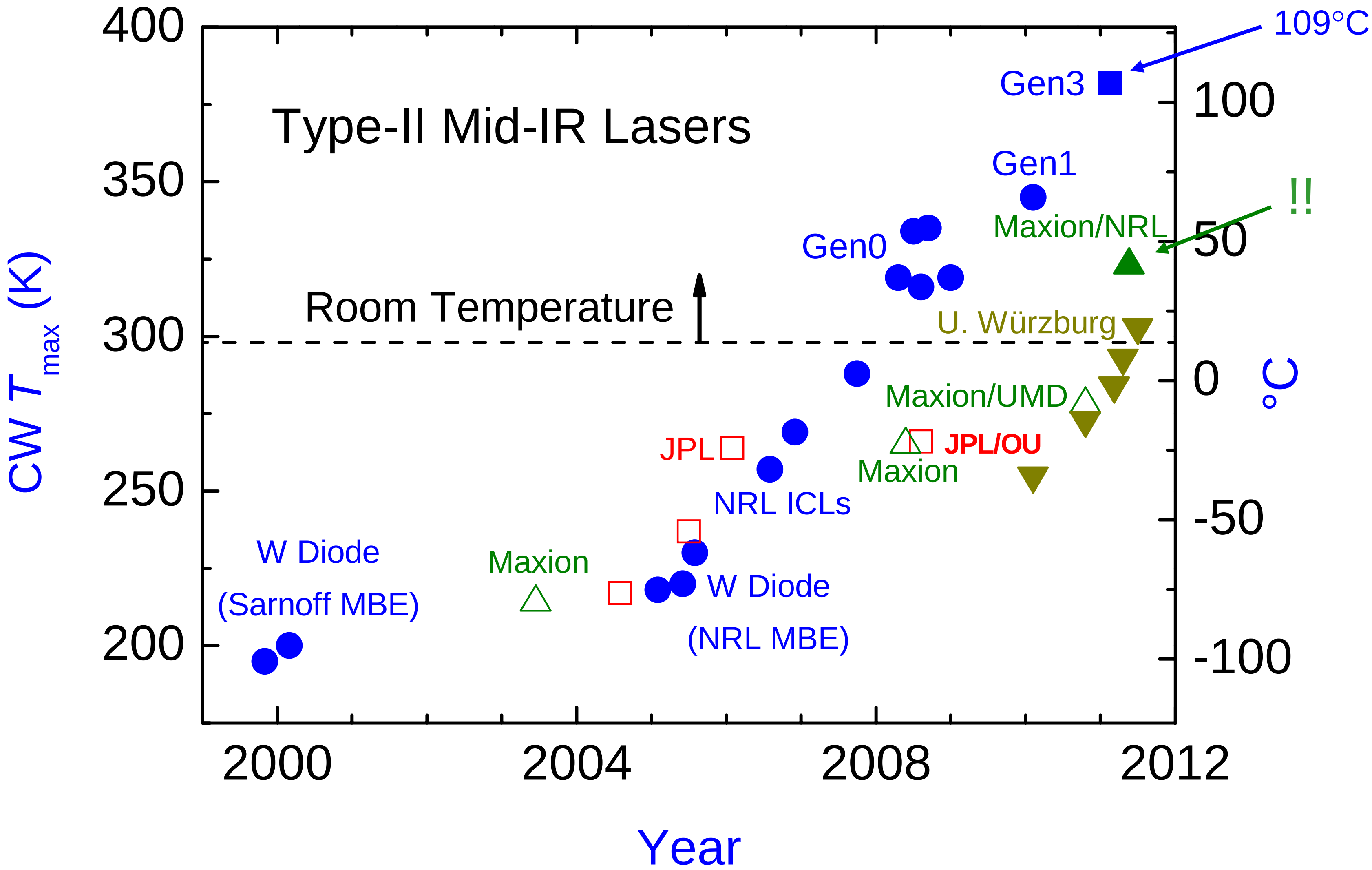
Record QCL value: $P_{th} \approx$ **10 kW/cm^2**

NARROW RIDGES: *CW TO EVEN HIGHER T_{max}*



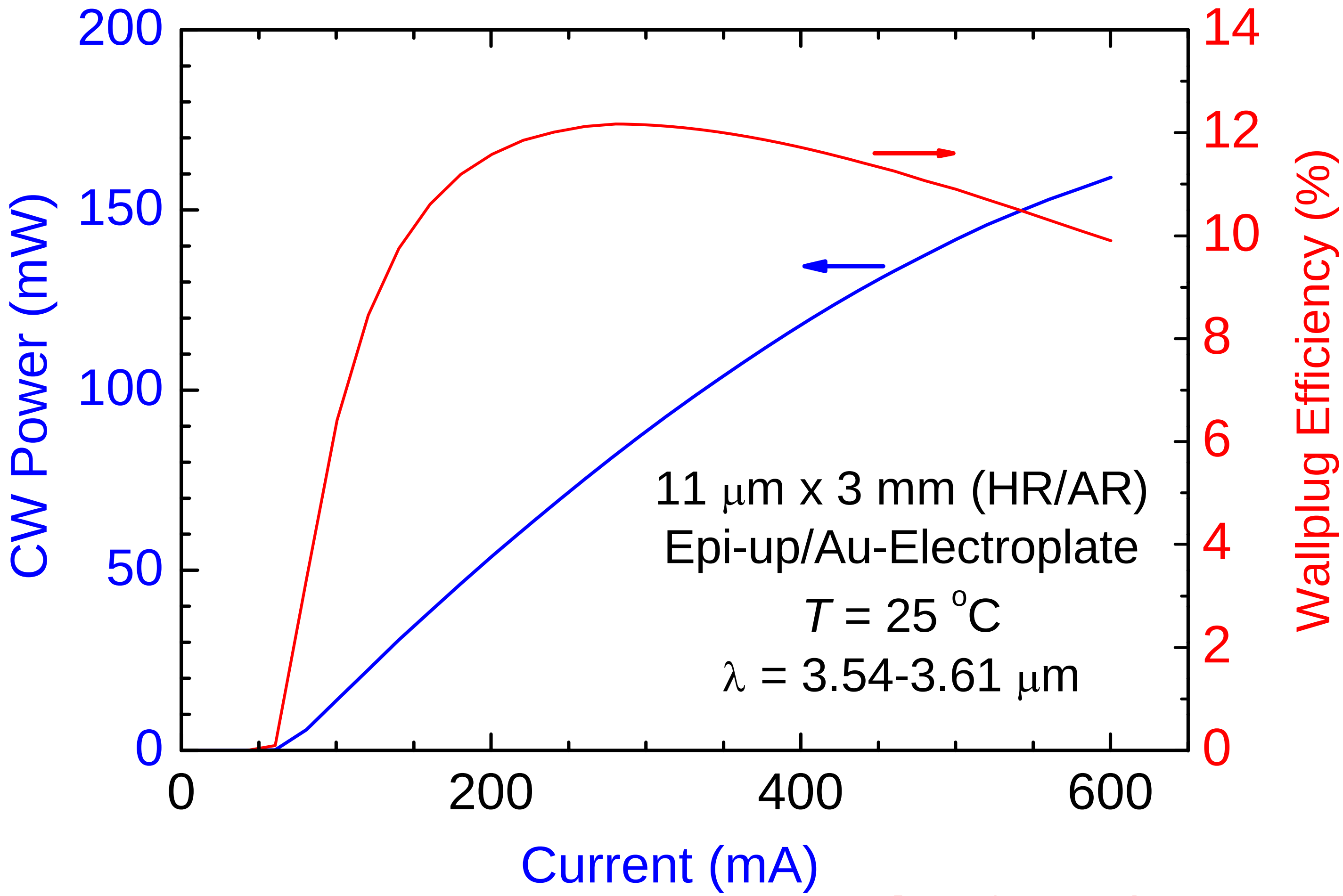
CW operation to 107 °C

HIGHER CW OPERATING TEMPERATURE



Also: **Maxion/PSI growth to NRL ICL design (Gen2) yielded nearly identical performance to NRL ICLs – Commercialization on the way!**

HIGH CW POWER & WALLPLUG EFFICIENCY



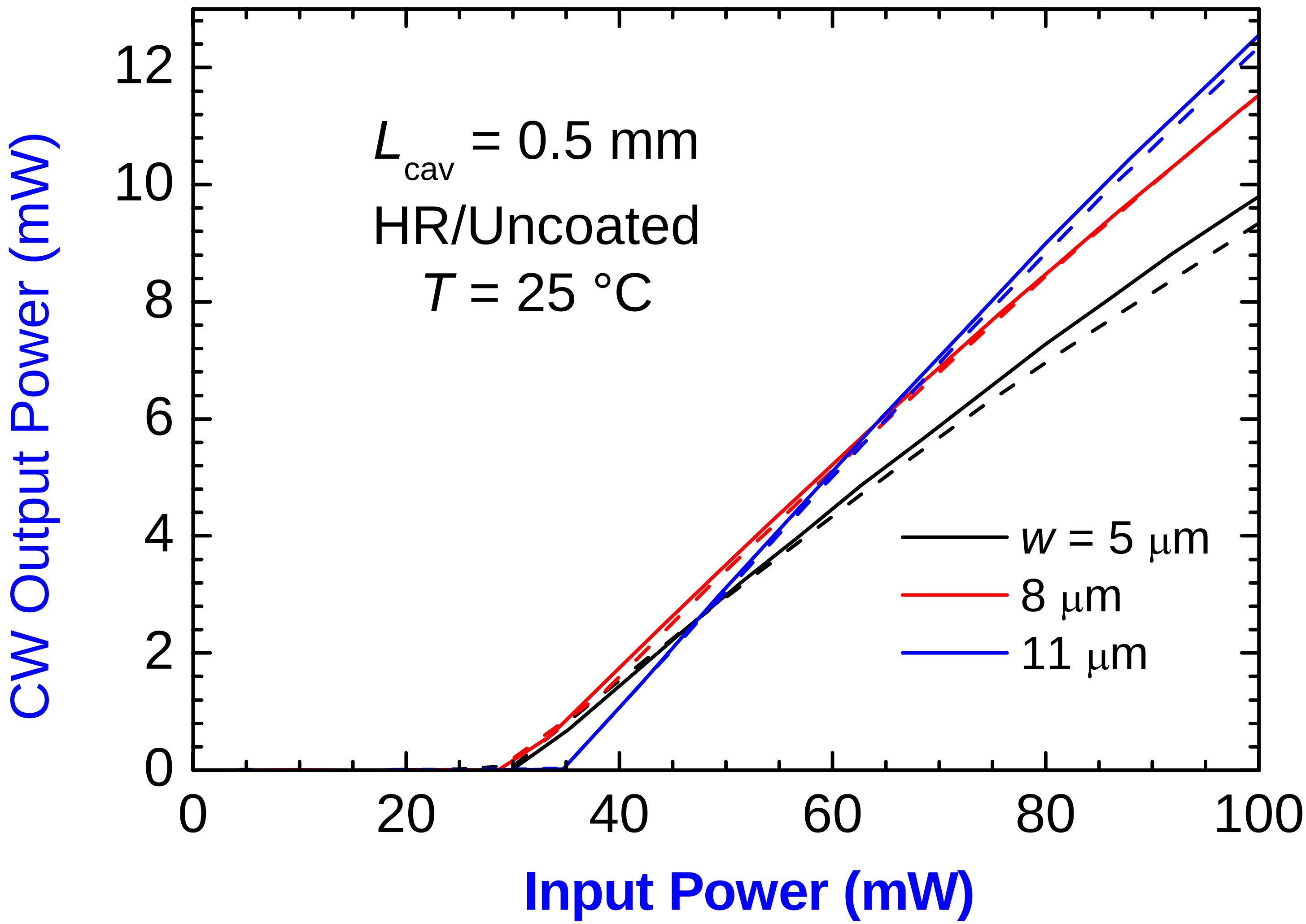
[Vurgaftman et al., Nature Com. 2, 585 (2011)

P_{max}^{cw} = 159 mW cw at room temperature (Beam quality $M^2 \approx 3$ @ $j > 10 \times j_{th}$)

WPE up to 12.2%, & still 9.9% at P_{max} (Shorter cavity: WPE = 13.5% @ 25 °C)

EXTREMELY LOW INPUT POWER THRESHOLD

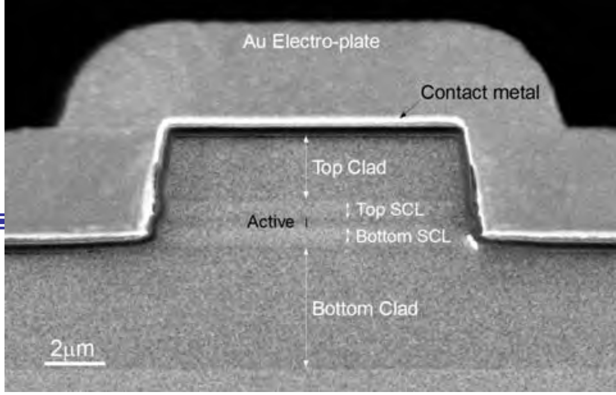
[Vurgaftman et al., Nature Com. 2, 585 (2011)]



T = 25 °C: Input for lasing < 30 mW

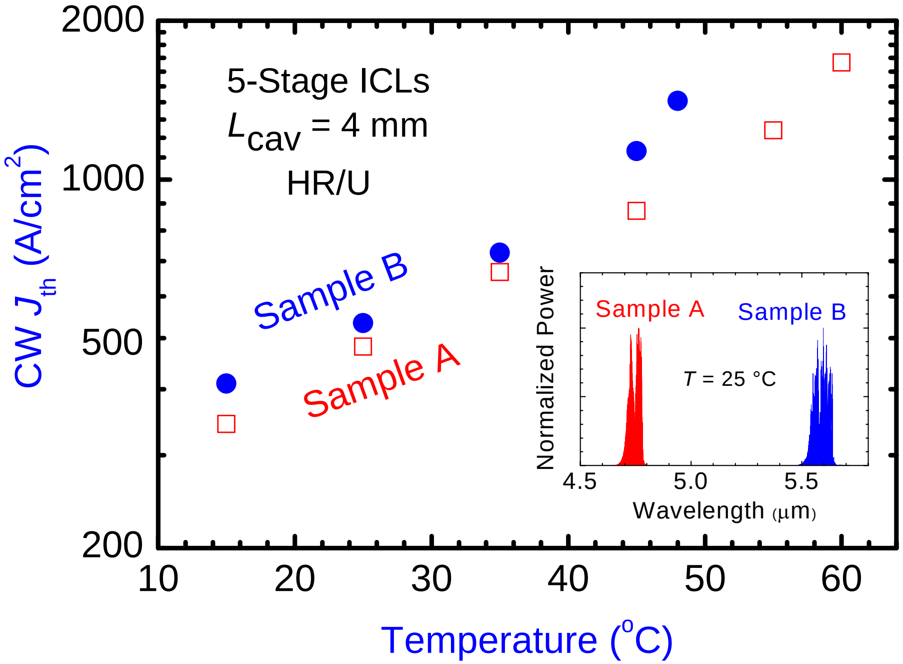
Best QCL value ever reported: 830 mW

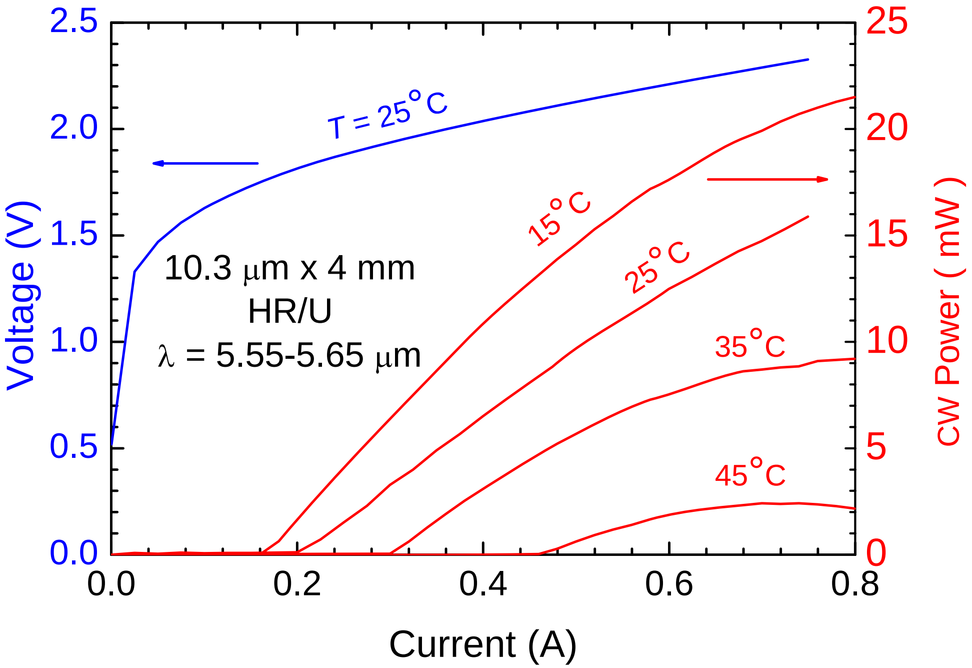
ROOM TEMP CW @ $\lambda > 4.5\ \mu m$



Narrow ridges processed from longest-λ wafers

Bewley et al., submitted to Opt. Expr.

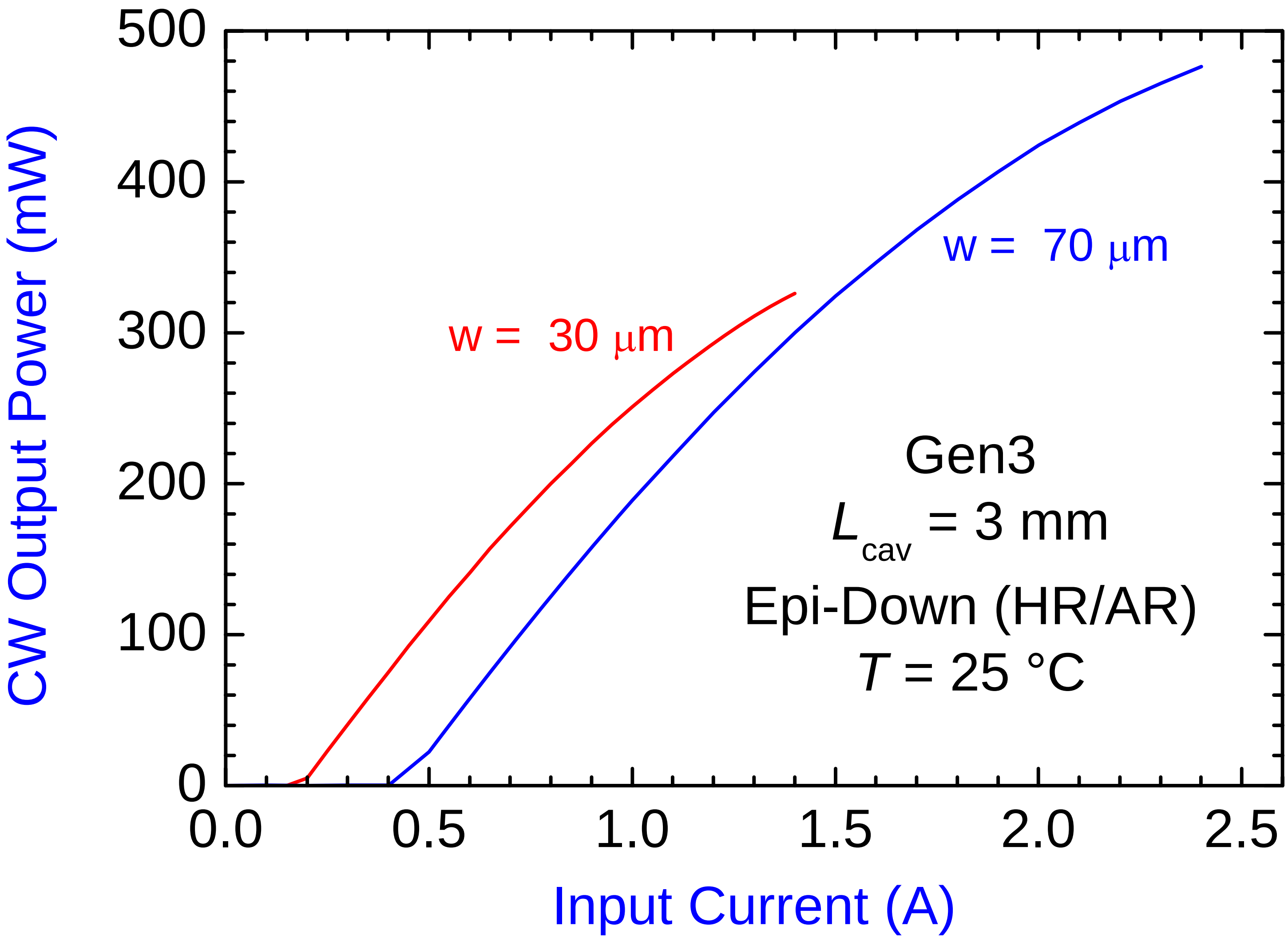




Both produced > 15 mW of cw power @ *T* = 25 °C

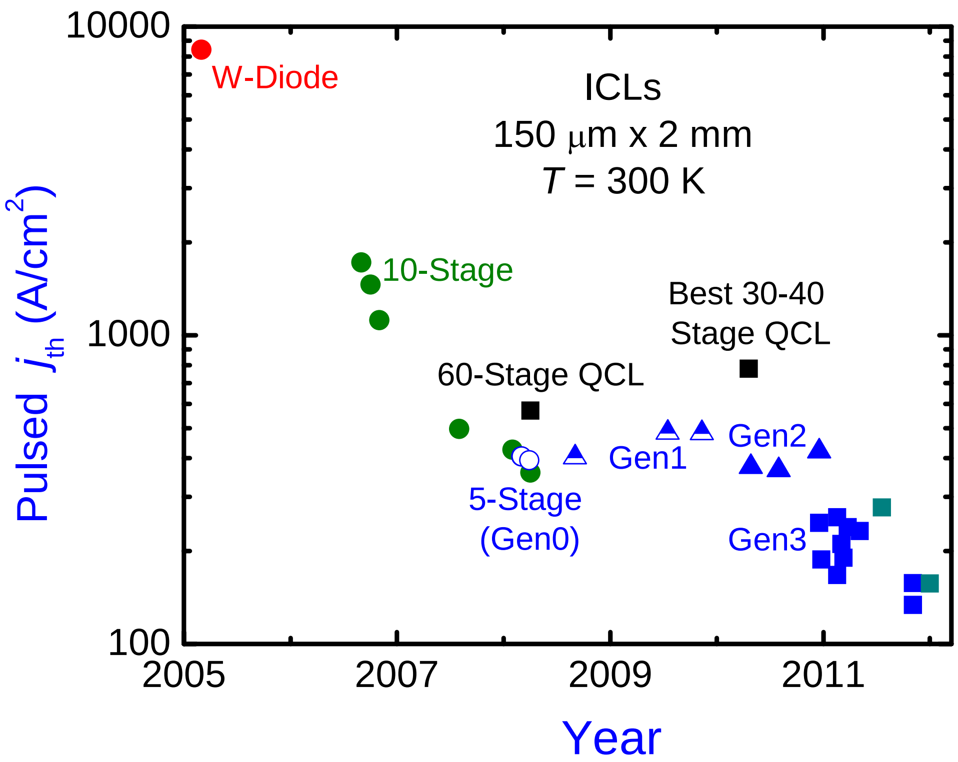
Operation to T_{max}^{cw} = 60 °C (4.9 μm) & 48 °C (5.7 μm)

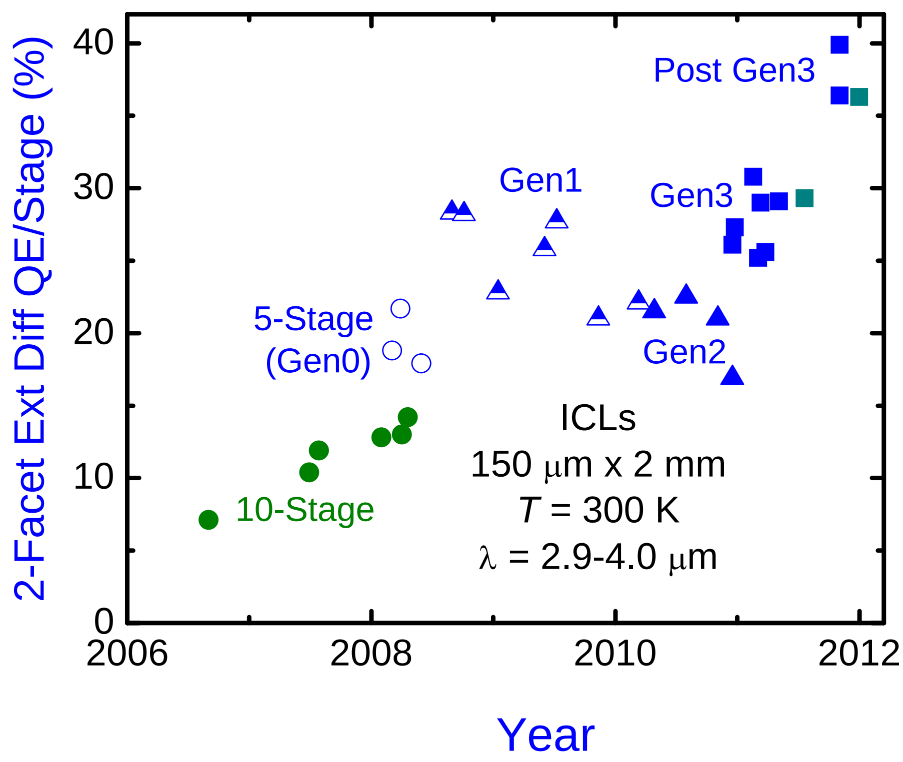
& THE LATEST:
EPI-DOWN MOUNTING (BROAD AREA)



P_{max}^{cw} > 470 mW at room temperature from 70-μm-wide ridge

NEW & IMPROVED WAFERS FROM 2 NRL MBEs

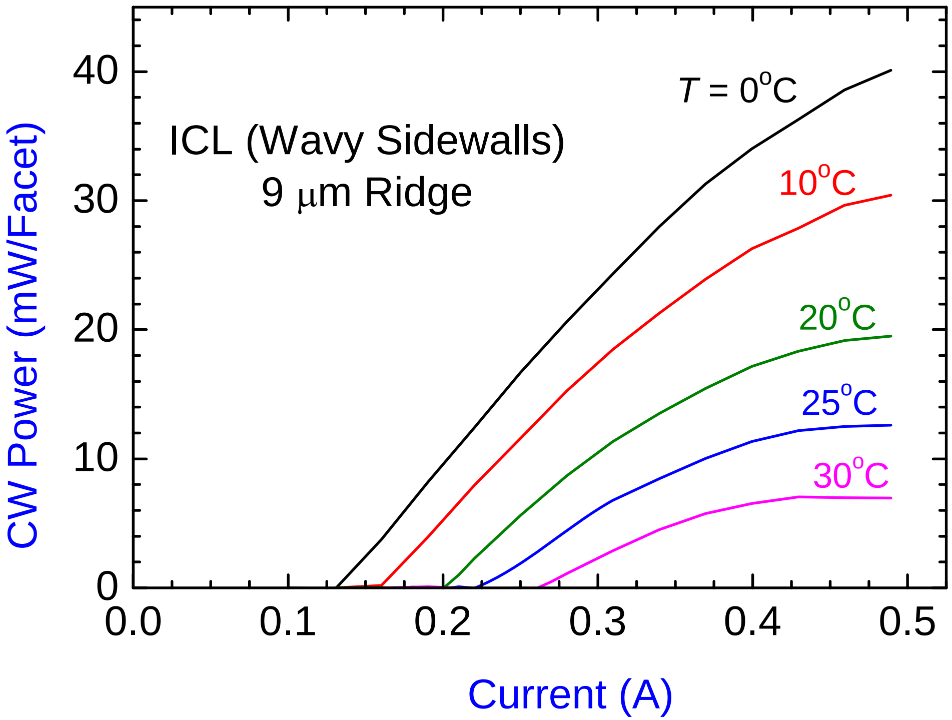


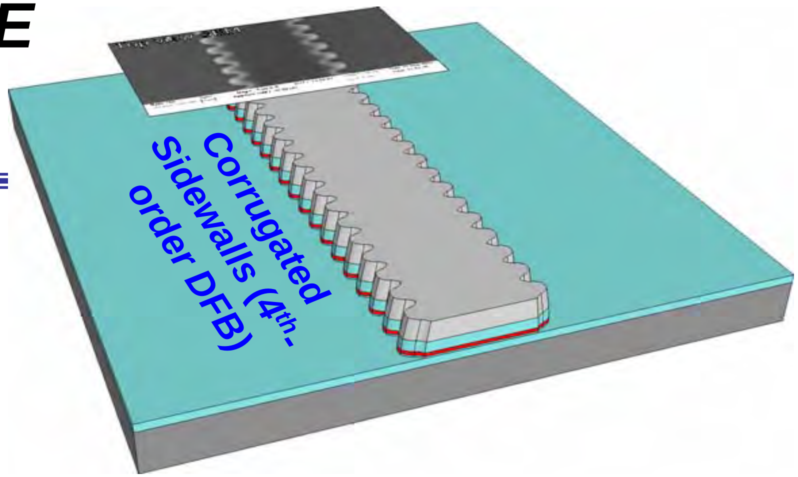


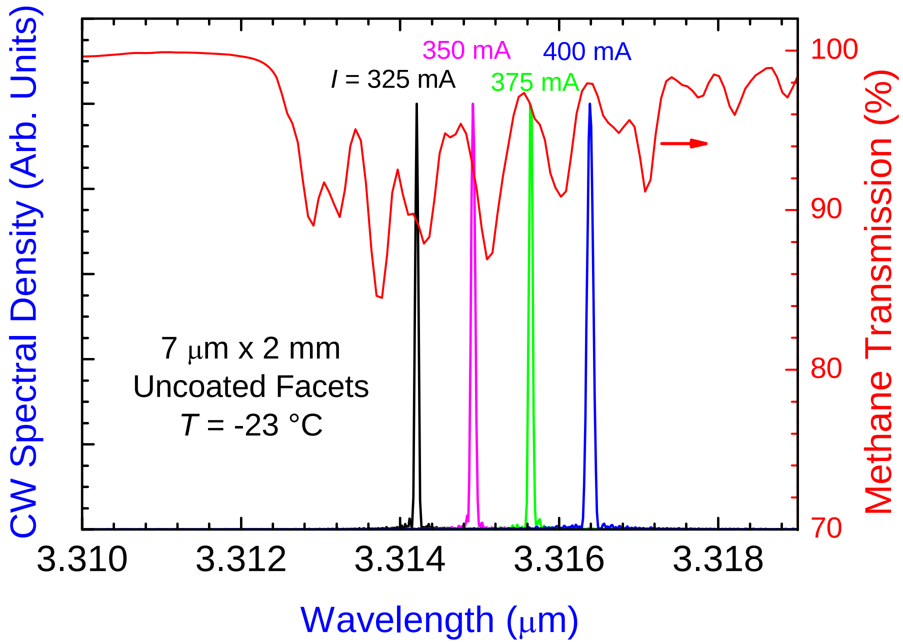
Thresholds dropped & efficiencies increased even further (Why?)

NARROW SPECTRAL LINE (Gen1 DEVICES)

C.S. Kim et al., APL 95, 231103 (2009)







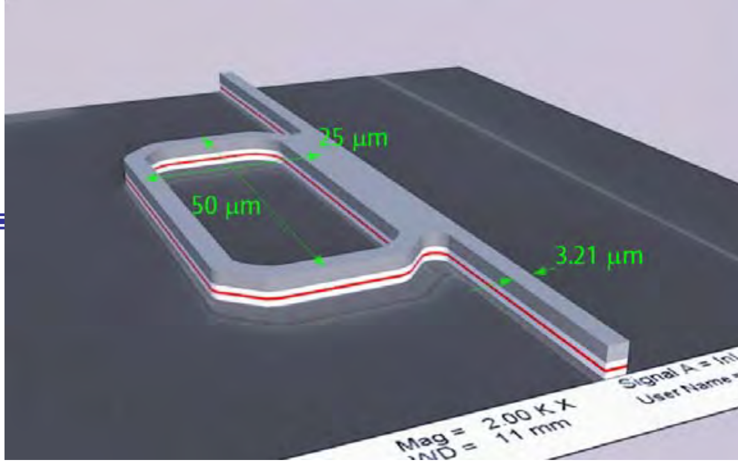
12 mW cw in single spectral line @ 25 °C; 29 mW @ 0 °C

Also:

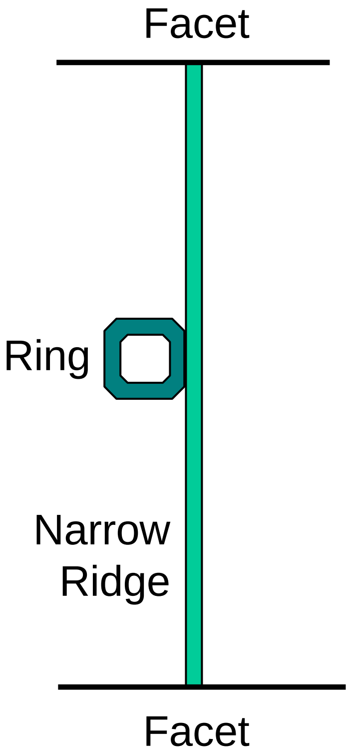
45 mW & 7.6% WPE in single mode @ -20 °C

Single-mode ridge spectrum, superimposed with methane absorption lines

RING RESONATOR ICLs

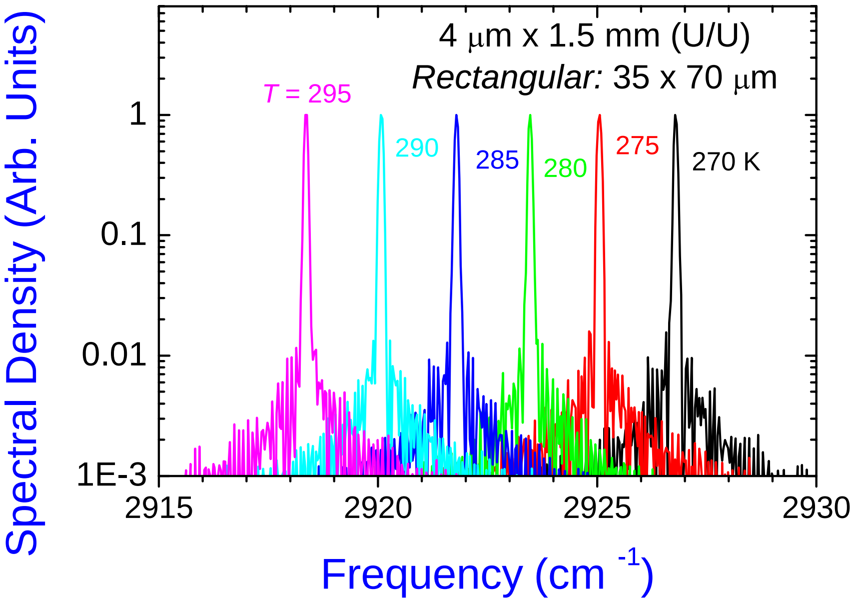


Coupled cavity lases on
Fabry-Perot & ring modes
coinciding closest to gain peak



Ring resonance selects single longitudinal mode

Single-Mode Output:



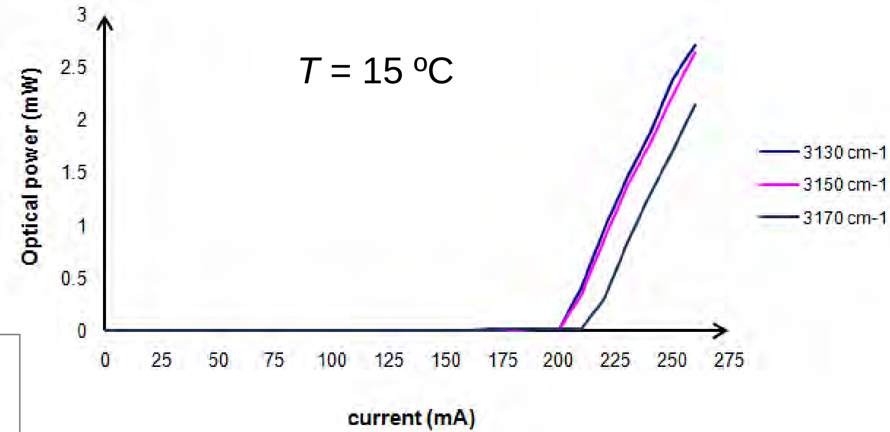
Narrow linewidth over extended temperature range –
Up to 5 mW cw output into single spectral mode at 2 °C

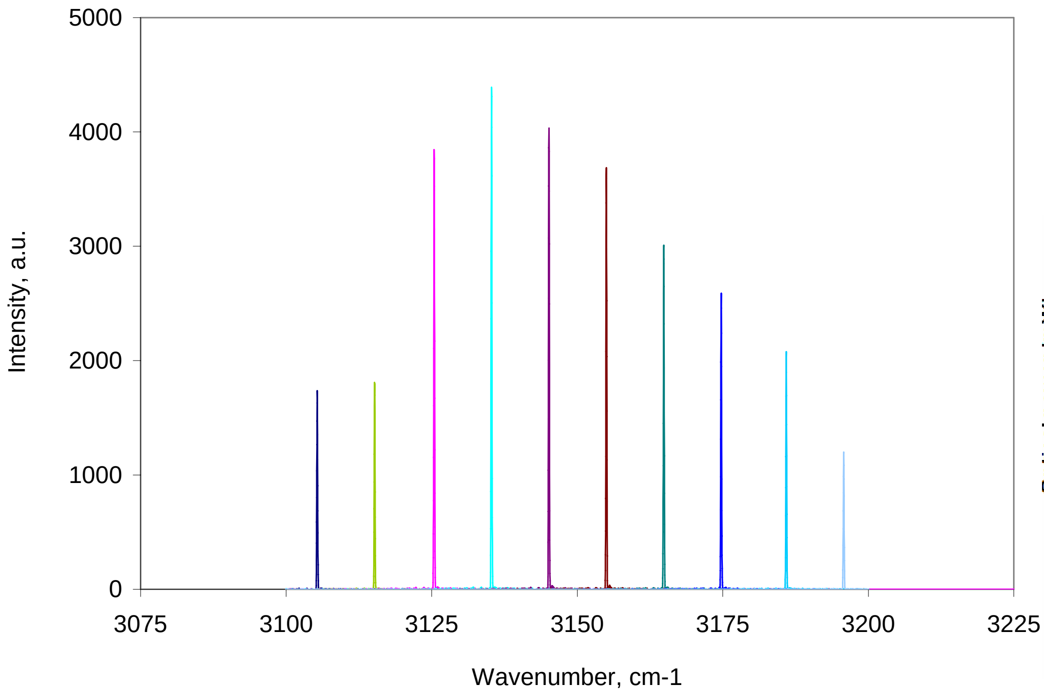
EXTERNAL CAVITY ICL

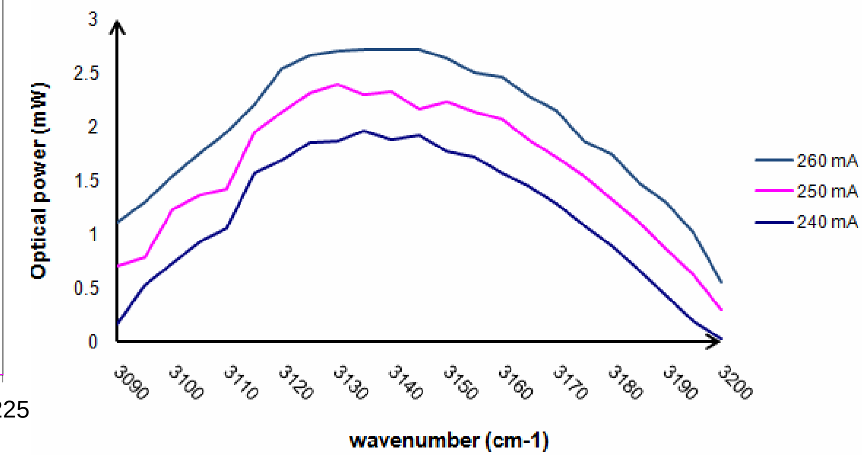
[with Daylight Solutions]

Caffey et al., Opt. Expr. 18, 15691 (2010)

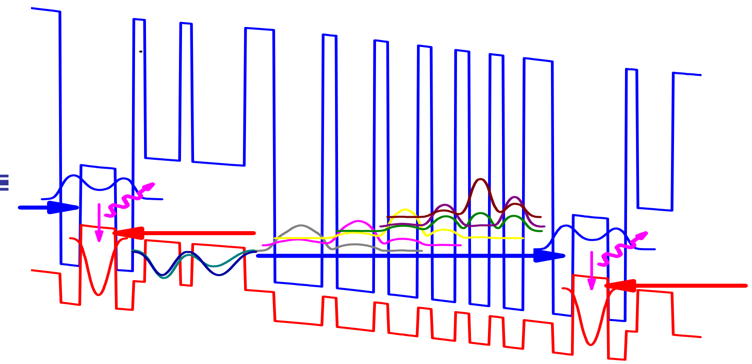
- Narrow linewidth in EC-ICL configuration
- 170 nm tuning range
- > 1 mW cw @ all λ (PA1 Generation)
- Low power consumption (< 1 W)



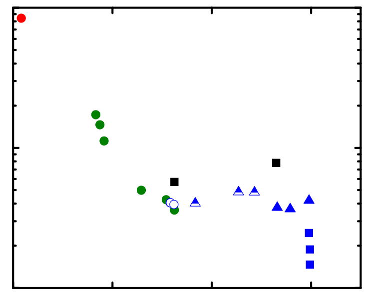




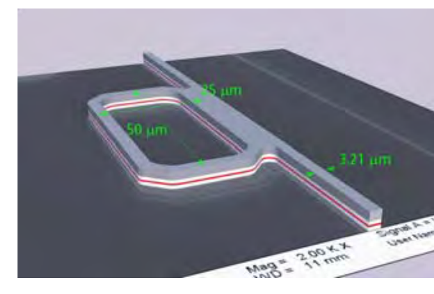
ICL STATUS



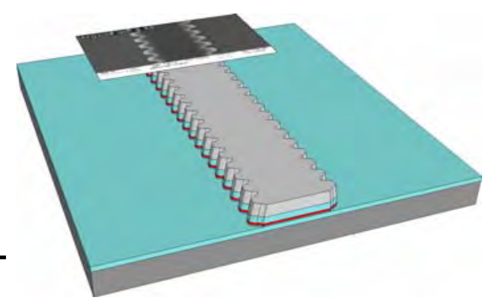
- High wafer yield despite design complexity
- Carrier rebalancing (Gen3) substantially improves all performance characteristics



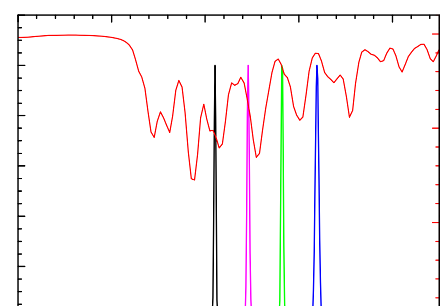
- *Low Input Power:* < 30 mW @ T = 25 ºC (RT) is > 25 x lower than best QCL result
  - Dramatic extension of battery lifetime
- *CW Narrow Ridges (Gen3):*
  - T_{max} = 109 ºC
  - *RT:* P_{max} = 159 mW, WPE = 13.5%, M^2 = 1.0-3.1



- *Latest wafers (Pulsed @ 300 K):*
  - j_{th} = 134 A/cm^2, EDQE = 40%



- *Corrugated-Sidewall DFB (Gen1):*
  - P_{max} = 12 mW in narrow line @ RT
- Wafers already on hand can provide RT cw @ λ spanning 2.9 to 5.7 μm



- ***Bottom line:*** **ICLs ready & able for field spectroscopy!**